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Advances in the Development of Radiometric Measurement System Applied to Power Circuit Breaker

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Abstract: Because the importance of the power circuit breaker for the liable operation of a power system added to the increasing demand for continuity in power delivery, non-invasive techniques for evaluating its condition have presented a significant evolution over the last five years. Today, the most promising technique is based on a radiometric system, which is based on analyzing the timing of the pole operation through the waveform of the transient signals radiated from the circuit breaker chambers, captured by sensors, and conveyed to a registering & processing unit. Even though this may seem to be a simple task it is rather far from being so as it is described and discussed in this work. Based on the experience of the authors, represented by several published papers about radiometry applied to power circuit breaker analyses, efforts towards the development of new equipment for replacing the commercially available digital oscilloscope became the milestone in the way to reaching a fully confident radiometric system. Although still much has to be done for this, important practical data are given over this work besides an approximate analytical approach for better comprehending the radiometry itself. The key issue is properly guaranteeing the registering of transient signals from the power circuit chambers when any switching is made, which has been shown as being a very challenging task. This work is intended to serve as a basic reference for every radiometric system applied to circuit breakers that may be in development.

Keywords: radiometry, circuit breaker, trigger, oscilloscope, antennas.

1. INTRODUCTION

Because of its fundamental role in guaranteeing the reliability of power system operation based on the endurance of switching current with high amplitudes power circuit breaker is prioritarily chosen as the equipment to be under maintenance. In this case, the main concerns with the power circuit breaker condition are regarding its capacity to properly interrupt any rated short-circuit current without any arc reignition, which would characterize the circuit breaker to be condemned and thus immediately replaced, representing a rather undesirable situation. For its turn and until today, for this maintenance, the circuit breaker must be periodically de-energized for the application of invasive maintenance techniques, which includes measurement of the contact electrical resistance besides other electrical, mechanical, and cleaning measures [1,2]. In its turn, for the sake of reliability on the power delivery, the time interval elapsed for performing any circuit breaker maintenance must be as short and effective as possible. Nevertheless, over the years these maintenance principles have been intensively contested by maintenance personnel of power utilities for being under pressure of increasing demand for power supply continuity.

Alternatively, combined with the mentioned contestation, the increase in the availability of computer tools, as the ATP and EMTP programs, a new technique for evaluating the actual condition of an operating power circuit breaker was developed, as described in [3]. In its essence, this new technique depends on modeling the electric circuit adjacent to the circuit breaker for studying their behavior under transient conditions of switching operation, which is known as TRV-Transient Recovery Voltage study. This sort of study is mainly based on the analysis of the instantaneous voltage developed between circuit breaker poles that should not surpass some pre-defined voltage values defined by some envelope curves [4]. Regarding this approach, although TRV studies based on computer simulations are accepted by many power utilities as being confident enough for evaluating the actual condition of a power circuit breaker, it is unavoidable to consider the inherent risks that it represents because of the strong dependence on detailed and accurately correct electric circuit modeling, which is not an easy task. Nevertheless, it must be emphasized the key advantage of this new method that is its non-invasive nature since there is no need to de-energizing the power circuit breaker.

Although TRV studies are today widely deployed and accepted, because of its drawback of risks due to the possibility of inaccurate circuit modeling the demand for more confident and non-invasive maintenance techniques applied to power circuit breakers contributed to the development of an even newer alternative technique for evaluating the actual condition of an operating power circuit breaker. This newest technique based on radiometry was proposed in [5], by representing a significant change in the approach for evaluating the condition of an operating power circuit breaker maintenance for being based on radiated signals from each of its operations.

Regarding radiometric measurement applied to the power circuit breaker, the analysis of its condition is based on measuring the time interval elapsed between any two successive poles opening/closing of the three phases, which is to be identifiable on the instantaneous voltage waveform obtained from the captured transient signal radiated from the circuit breaker chambers. For the pole opening the more the value of the mentioned time interval worse the pole contact status because of the evidence of hindering in the arc quenching. Therefore, capturing elements as antennas or sensors enable the irradiated signals to be conveyed to recording & processing equipment. In turn, there must be very sensitive coordination between transient signal recording and the circuit breaker switching because of the intrinsically very short time of the transient signal existence. Thus, for performing both recording and processing of the captured signal digital oscilloscope is a natural immediate choice as equipment to be adopted because of its usual availability in triggering electrical transient events. Therefore, first-generation arrangements of radiometric systems applied to circuit breaker are often centered on a commercially available oscilloscope connected to antennas through coaxial cables. Nonetheless, some key drawbacks are immediately identified as reasons for the search for alternative arrangements. Namely, the vulnerability of the embedded trigger function when registering transient signals radiated from the circuit breaker chambers and its limited adjust availability for properly registering these signals. Moreover, the susceptibility of the oscilloscope to the electromagnetic interference inherently existent in a power substation environment can not only harm the oscilloscope itself as well as it may also cause an undesired trigger. Based on this, some efforts have been made by the authors in a search for capturing devices other than antennas in view of optimizing the behavior of the oscilloscope trigger function, as in [6]. Instead, after a set of laboratory tests it could be clear that some new registering equipment should replace the commercially available oscilloscope. In the meantime, even a signal analyzer was tested but the mentioned vulnerability remained, which pointed out the need for the development of new and dedicated registering equipment. This new equipment is a second-generation radiometric system applied to the circuit breaker and is under tests running in power substations for adjusting its features in view of fully guaranteeing the registering of transient signals radiated from the circuit breaker chamber during each of its rare and programmed operations.

Thus, by culminating with a presentation of some promising results obtained from the deployment of the radiometry system of the second generation in tests run in a power substation, from now on this work presents a driven description of the basic features of power circuit breaker followed by an analytical approach to help in the comprehension of radiation principles and thus followed by the description of important achievements obtained during the enhancement of the radiometric system. The presented results are intended to be helpful for researchers who may be involved in developing similar radiometric systems.

2. KEY FEATURES OF THE POWER CIRCUIT BREAKER

The power circuit breaker is a very crucial component of a power system because of its capability in interrupting or applying current with significant amplitude in a reliable way. Even though there is a myriad of types of this equipment widely deployed in power systems, this is a sort of equipment to which not many designers are dedicated, in comparison to power transformers or synchronous machines, for example. One of the possible reasons may rely on the fact that because of the inherent presence of an electric arc to be quenched, designing a power circuit breaker requires simultaneous deep knowledge in both mechanical and electrical engineering, with emphasis on plasma dynamics, heat diffusion and radiation and statics & dynamics of metallic structures from the mechanical engineering and electric arc processes, electric field grading and electric charging of dielectric surfaces from the electrical engineering. By the way, these are some reasons for the existence of different types of circuit breakers based on the dielectric material deployed in the chamber in view of arc quenching that may be compressed air, mineral oil, and SF6, among others less usual. In addition, it must be considered the non-linearity in the electrical behavior of the arc, which makes power circuit breaker design to be rather complex. For further details on power-circuit breaker design, some suggested references are [7,9]

So, the combination of the described features and the inherent increase in power demand justifies why a power circuit breaker must have its operating condition periodically evaluated. On the other hand, it is hard to define accurately the period for this evaluation because of the inherently stochastic nature of the point of the sinusoidal voltage or current at which the contacts of the power circuit breaker poles will start to unite or separate. This means that arcs with different values of the time interval of existence are decisive for compromising the circuit breaker status. Therefore, radiometric measurements that have been shown as being a promising technique for enabling the definition of the right time for the maintenance of the circuit breaker to take place have some barriers to be overcome, yet. This is what is presented and proposed in this work, in which some key achievements in the second generation of radiometric systems applied to circuit breakers are evidenced.

3. RADIATION PRINCIPLES

For understanding the principles of radiometry, in which electromagnetic signals radiated from the operation of a power circuit breaker are captured by antennas located around the arc quenching chambers of a circuit breaker, consider Fig. 1, in which it is suggested that the irradiated signal form an operating circuit breaker chamber can be compared to a dipole antenna operation with a sinusoidal injection of signal to be transmitted.

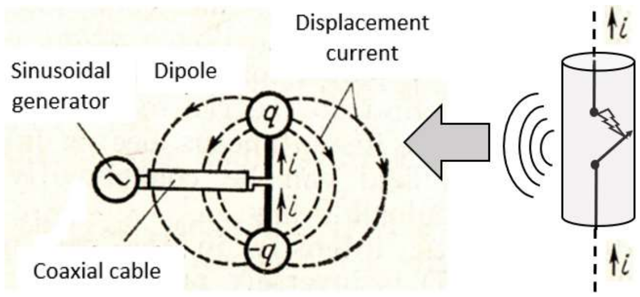


Fig. 1. Radiated signal from the chamber of an operating power circuit breaker and its resemblance to a dipole antenna radiating a sinusoidal signal

In this case, due to the favorable geometry, spherical coordinates are used to analyze the behavior of magnetic and electric fields that are originated from the current, i, of an elementary section of the antenna, dl, as shown in Fig. 2 and adapted from [10].

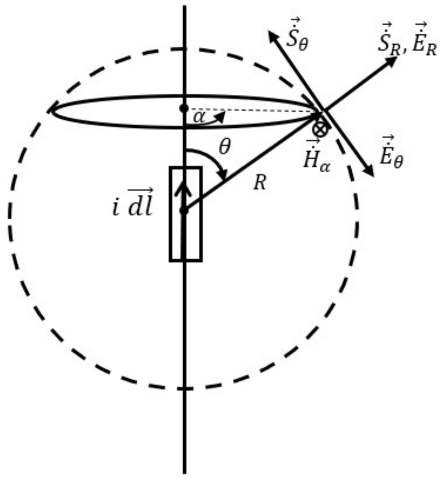


Fig. 2. Application of spherical coordinates to analyze the behavior of the dipole antenna

The elementary sinusoidal current segment, *i dl*, will give rise to an angular component of the magnetic field, $\dot{\vec{H}}_\alpha$, an azimuthal, and a radial component of the electric field, $\dot{\vec{E}}_\theta$, and $\dot{\vec{E}}_R$, respectively. Thus, the power density of the irradiated signal, which is the Poynting vector, has two components, $\dot{\vec{S}}_R$, and $\dot{\vec{S}}_\theta$. Besides the value of its amplitude, which is the power density of the irradiated signal, the Poynting vector also allows us to understand how receiver elements can be properly adopted and positioned at a distance from the dipole antenna for being more efficient in capturing the propagating signal.

Initially, by considering a sinusoidal current flowing through the dipole antenna length segment, in Fig. 2, the value of the elementary magnetic field vector, $d\dot{\vec{A}}$, is

$$d\dot{\vec{A}} = \frac{\mu_o}{4\,\pi} \frac{I_m\, e^{j\omega\left(t-\frac{R}{u}\right)}}{R}\, \overrightarrow{dl} \tag{1}$$

in which $I_m\, e^{j\omega\left(t-\frac{R}{u}\right)}$ is the phasor representation of the current i(t) = $I_m sen\left[\omega\left(t-\frac{R}{u}\right)\right]$,whereas t is the time, in seconds, R is the radial distance to the elementary segment, in meters, u is the value of the speed of light, in m/s, ω is the angular frequency , in rad/s, and μ_o is the magnetic permeability of the vacuum. In turn, the difference $\left(t-\frac{R}{u}\right)$ denotes the establishment of standing waves and the phase difference due to their propagation at the speed of light, at each point of radial distance R from the elementary segment carrying the current.
So, considering that the magnetic field, $\vec{H}$ is related to the magnetic field vector $\vec{A}$ in the following way

$$\vec{H} = \frac{\vec{\nabla} \times \vec{A}}{\mu_o} \quad (2)$$

and that because of Ampère´s law, only its angular component, α, exists, in spherical coordinates, the magnetic field vector will be given by

$$\dot{\vec{H}}_\alpha = \frac{\dot{I}_m \, sen\theta}{4\,\pi R} \left[\frac{1}{R} + j\frac{\omega}{u}\right] e^{j\omega\left(t - \frac{R}{u}\right)} dl\, \hat{\alpha} \quad (3)$$

or, in the time domain,

$$\vec{H}_\alpha(t) = \frac{I_m \, sen\theta}{4\,\pi\, R} \left\{\frac{sen\left[\omega\left(t - \frac{R}{u}\right)\right]}{R} + \frac{\omega \cos\left[\omega\left(t - \frac{R}{u}\right)\right]}{u}\right\} dl_{\,\hat{\alpha}} \quad (4)$$

For the electric field, $\vec{E}$, it can be obtained from

$$\dot{\vec{E}} = \frac{1}{j\omega\varepsilon_o} \nabla \times \dot{\vec{H}}_\alpha \quad (5)$$

Thus, there will be components, R, and θ, for the electric field, given by

$$\dot{\vec{E}}_R = \frac{I_m cos\theta}{2\pi R^2 \varepsilon_o} \left[\frac{1}{u} - j\frac{1}{R\omega}\right] e^{j\omega\left(t - \frac{R}{u}\right)}\, dl_{\,\hat{R}} \quad (6)$$

for the radial component which, in the time domain, becomes

$$\vec{E}_R(t) = \frac{I_m cos\theta}{2\pi R^2 \varepsilon_o} \left[\frac{sen\left[\omega\left(t - \frac{R}{u}\right)\right]}{u} - \frac{cos\left[\omega\left(t - \frac{R}{u}\right)\right]}{R\omega}\right] dl_{\,\hat{R}} \quad (7)$$

while the azimuthal component becomes

$$\dot{\vec{E}}_\theta = \frac{I_m \, sen\theta}{4\pi R\varepsilon_o} \left[\frac{1}{uR} + j\left(\frac{\omega}{u^2} - \frac{1}{\omega R^2}\right)\right] e^{j\omega\left(t - \frac{R}{u}\right)}\, dl_{\,\hat{\theta}} \quad (8)$$

which looks like this in the time domain

$$\vec{E}_\theta(t) = \frac{I_m \, sen\theta}{4\pi R\varepsilon_o} \left\{\frac{sen\left[\omega\left(t - \frac{R}{u}\right)\right]}{uR} + \left(\frac{\omega}{u^2} - \frac{1}{\omega R^2}\right)\frac{\cos\left[\omega\left(t - \frac{R}{u}\right)\right]}{u}\right\} dl_{\,\hat{\theta}} \quad (9)$$

Thus, for obtaining the expression of the Poynting vector, S ⃗(t), the following vector product is to be done

$$\vec{S}(t) = \left(\vec{E}_R(t) + \vec{E}_\theta(t)\right) \times \vec{H}_\alpha(t) \quad (10)$$

that becomes

$$\begin{aligned}\vec{S}(t) = \frac{(I_m\, dl)^2}{32\varepsilon_o(\pi R)^2} \Bigg\{ & -\left[\frac{sen2\theta}{R}\left(\frac{sen\left[\omega\left(t - \frac{R}{u}\right)\right]}{u} - \frac{cos\left[\omega\left(t - \frac{R}{u}\right)\right]}{R\omega}\right)\right]_{\hat{\theta}} \\ & + \left[(1 - cos2\theta)\left(\frac{sen\left[\omega\left(t - \frac{R}{u}\right)\right]}{uR} + \left(\frac{\omega}{u^2} - \frac{1}{\omega R^2}\right)\frac{\cos\left[\omega\left(t - \frac{R}{u}\right)\right]}{u}\right)\right]_{\hat{R}} \Bigg\} \\ & \times \left(\frac{sen\left[\omega\left(t - \frac{R}{u}\right)\right]}{R} + \frac{\omega \cos\left[\omega\left(t - \frac{R}{u}\right)\right]}{u}\right)\end{aligned} \quad (11)$$

Based on (4), (6), and (8), it is noticeable that the amplitude of the components of the magnetic and electric fields that radiate from the current element presents a dependence on the inverse proportion of the radial distance, R. This dependence is proportional to the first, second or third power. On the other hand, from (11) it can be seen that for the power density of radiated signal, the dependence on the inverse of the radial distance is proportional to the second, third, and fourth power. Because of this form of dependence, concepts such as "near-field" and "far-field" are defined for a certain frequency range. In turn, for radiometric analysis of a circuit breaker, for which the near field condition is considered, these expressions are useful for the choice between a magnetic or an electric field-based antenna for playing the role of a signal-capturing sensor device. Nonetheless, it is important to consider that these expressions have limited validity because the circuit breaker chamber itself does attenuate the amplitude of the radiated signal. Moreover, the presented analysis is based on a unique value for the angular frequency of the sinusoidal current whereas the electric arc has a range of different frequencies. Thus, for more accurate analyses the Fourier transform of the electric arc signal in the time domain should be considered and superimposition of effects should be applied.

Finally, in addition to the dependence on the frequency of the conducted current and the radial distance, for the circuit breaker radiometry, it is also important to consider the value of the azimuth angle, θ, as it implies in defining the preferred positioning for the sensor element to be used as capturing device. For this purpose and based on Fig. 2, by starting with the magnetic field, expressed in (4), it is noted that since its amplitude depends directly proportional to the sine of the azimuth angle, θ, it is deduced that the azimuthal angle of the preferential positioning of the sensor of the magnetic field has 90 degrees. Thus, angles close to 180 and 0 degrees are to be avoided. As for the electric field, the radial component, described in (7), has an amplitude value directly proportional to the cosine of the azimuthal angle, which implies an inversion of the preferential positioning of the electric field sensor, compared to that deduced for the magnetic field. However, it is important to consider that this radial electric field component decreases very quickly with the radial distance from the current element, which makes its importance somewhat secondary. On the other hand, as for the azimuthal component of the electric field, as in (8), this shows a smaller decrease in amplitude as a function of the radial distance and dependence directly proportional to the sine of the azimuthal angle, θ, which indicates a suggestion of positioning of the electric field sensor similar to the one made for the magnetic field sensor.

4. DEVELOPMENT IN RADIOMETRY APPLIED TO POWER CIRCUIT BREAKER

As presented in [11], the basic arrangement of a radiometric system applied to a power circuit breaker is shown in Fig. 3, in which the transient signal radiated from each of the three-phase chambers of a circuit breaker operation is picked up by the capturing device, converted into a voltage signal, and conveyed to the measurement unit through a coaxial cable in view of being detected and properly registered. This transient signal is superimposed to the EMI signal inherently present in the whole environment of a power substation with the predominance of power frequency signal.

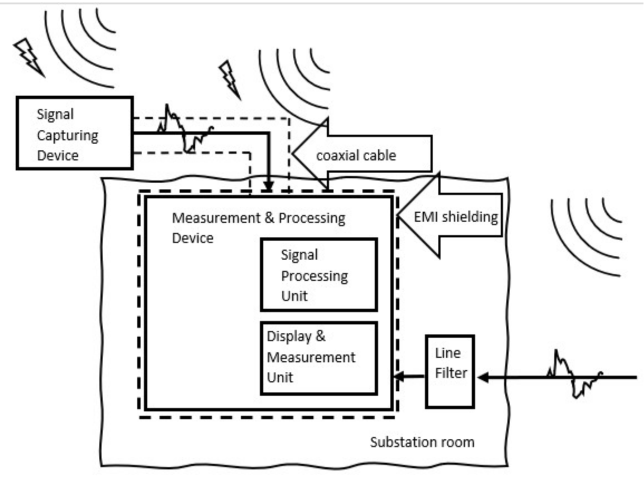


Fig. 3. Basic arrangement of a radiometric system – Electromagnetic transient signal radiated from the chambers of the power circuit breaker is picked up by the signal capturing device and conveyed by a coaxial cable to the Measurement & processing unit

With the aim of showing how the deployment of a radiometric system to a power circuit breaker can be, Fig. 4[11] shows three capacitive antennas aligned to each of the three-phase circuits of a 230 kV power substation yard. It is important to notice that the position of any of the antennas cannot violate any of the required clearance distances when installed. In this case, as a measure for the signal trigger not being subject to the inherent power frequency noise, a fourth antenna was deployed. This antenna was an RF dipole antenna, and it was intended to capture only the high-frequency transient signals from the circuit breaker operation for triggering the signal registering. Thus, since it does not capture the power frequency noise interference that is inherently present it prevents such a sort of signal may cause any undesirable triggering. Although this antenna is not distinguished in Fig. 3, it is a signal-capturing device, in the same way, are the three capacitive antennas.

Still, concerning Fig.3, coaxial cables are not so evidently shown in Fig. 4 whereas the workbench oscilloscope adopted as measurement & data processing unit was not shown for being installed in the power substation room.

Fig. 4. Practical deployment of the arrangement of a radiometric system – antennas are dully placed on the ground of a 230 kV power substation yard [11]

Thus, as also presented in [11], Figs. 5 and 6.a to 6.c show the waveform of the registered signal radiated from the power circuit breaker chambers during a closing operation of the power circuit breaker. The graphic of Fig. 5 corresponds to the triggering signal picked up by the RF dipole antenna, whereas those of Figs. 6.a to 6.c correspond to the signal waveforms of each of the three phases captured by the capacitive antennas.

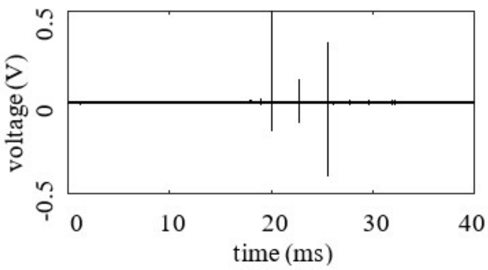
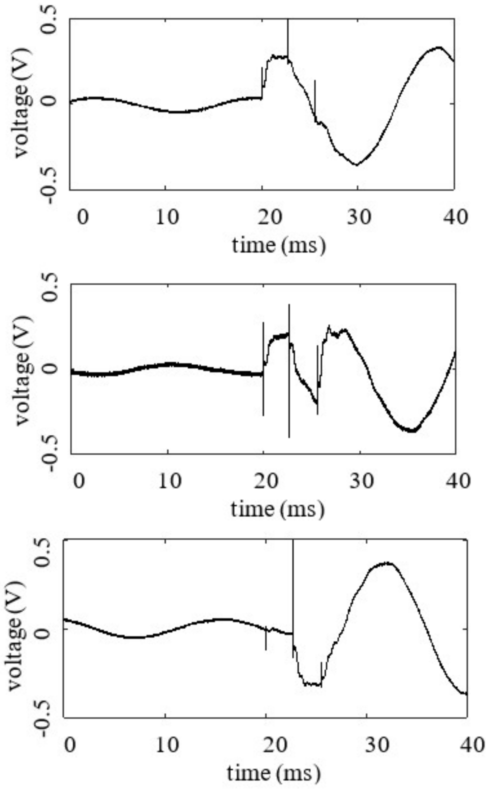


Fig. 5. Irradiated RF pulses captured by the RF dipole antenna during the closing operation of the circuit breaker



Figs. 6.a to **6.c**.Signal waveforms of captured by the capacitive coupling antennas during the closing operation of the circuit breaker. Phases A, B, and C, respectively

The presented waveforms represent what can be typically expected for the closing operation. Initially, the signal waveform of Fig. 5 which is from the RF dipole antenna is free from any power frequency signal but shows only three high-frequency pulses that correspond to the current interruption in each of the three phases. The first of these pulses triggered the registering of the captured signal. On the other hand, regarding Figs. 6.a to 6.c, it is noticeable the occurrence of those same three high-frequency pulses but superimposed to power frequency signal captured by the capacitive antennas. Based on the analysis of the behavior of the power frequency signals, it seems that the closure of the poles of phase A is the first one followed by phases C and B, respectively. By the way, this last one presents a signal waveform that is significantly interfered with by signals from phases A and C until it may become steady. In turn, all three phase chambers radiate high-frequency pulses that are mutually picked up by the antennas and each of these pulses is associated with a pre-arcing activity during the displacement of pole contacts [12].

These presented results represent a very successful and stimulating case of data acquisition. Nonetheless, in any of the programmed tests in the power substation, the success in triggering signals from each of the rare circuit breaker operations was not plain. At that time, the suspects were on the adopted antennas that would be very sensitive to their correct positioning combined with the stochastic nature of the intensity of the radiated signal because of the dependence of this intensity on the instant of the sinusoidal current or voltage at which the switching operation is made.

Thus, as presented in [6], an attempt for finding an adequate signal-capturing device was done with a Rogowski coil-based ferromagnetic device. For this, a set of tests was performed in the High-Voltage Laboratory of the University of Blumenau with several switching operations of a 35 kV / 800 A, oil chamber, Sprecher & Schuh ® three-phase MV circuit breaker fed by a low voltage/high current transformer. Reasons for this choice were its smaller dimension that facilitates its positioning on the ground of the substation yard, low cost, and likely enhancement in the increase in the amplitude of the picked-up signal for capturing both magnetic and electric radiated fields.

The main result of that attempt is that the key issue to be addressed was not on the capturing device but on the triggering principles of the commercially available oscilloscope combined with the above-mentioned inherently stochastic nature of the intensity of the radiated signal. Fig. 7, adapted from a similar one in [6] help to comprehend one of the many possible reasons for some of the circuit breaker operations not causing the oscilloscope triggering. It shows two superimposed different signals, A and B. Both signals are composed of a power frequency sinusoidal signal added to a sort of impulse voltage that is irradiated from the opening of a circuit breaker. The sinusoidal aspect of these signals represents the inherent interfering signal that is in the environment of a power substation. Thus, since the aim is in registering the transient voltage, the trigger level of the oscilloscope is set to a value that is greater than that of the sinusoidal amplitude. Thus, for signal A the peak of the transient voltage impulse is enough to reach the trigger level set by the operator. Therefore, this signal is very likely to cause oscilloscope triggering. On the other hand, for signal B the peak is not enough to reach the trigger level and thus it would very rarely cause the oscilloscope trigger.

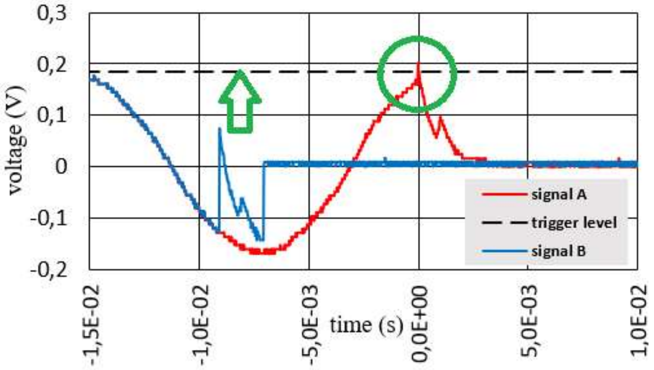
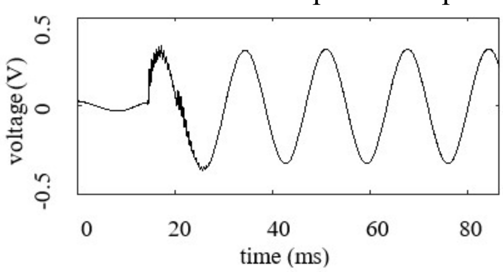
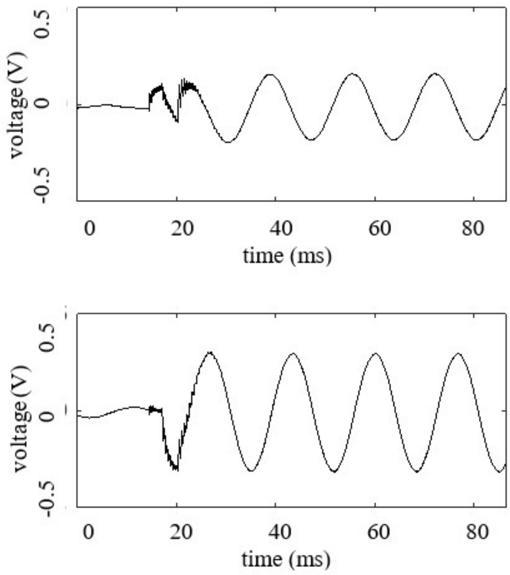


Fig. 7. Signal waveforms coupling antennas during the closing operation of the circuit breaker

Therefore, it became clear that the reason for missing those rare events of circuit breaker operation was not on the signal-capturing device but on the trigger principles adopted by the commercially available oscilloscopes, which is essentially the same one adopted by the signal analyzers. Therefore, the only option was to develop new equipment, which represents a milestone in the development of the radiometric system applied to circuit breakers by the research group.

As presented in [11], the newly developed equipment for replacing the oscilloscope is based on the time rate of the sampled signal that is obtained from the analogic signal that is picked up by the capturing device and conveyed to it where it is discretized. Thus, when in the substation test the operator adjusts the minimum level of triggering with the basis of the time derivative of the signal picked up by the capturing device. Moreover, because of the importance of evaluating the time interval elapsed between every two subsequent phases' current interruption or application additional data processing through wavelet transform has been implemented. As an example of how the newly developed equipment can properly replace the commercially available oscilloscope, Figs. 8.a to 8.c show the results of the most recent tests performed in a 230 kV power substation. Specifically, results are from the closing operation of a power circuit breaker and those same passive capacitive antennas were deployed.





Figs. 8.a to **8.c**. Signal waveforms of the captured and registered for the closing operation of a circuit breaker. Phases A, B, and C, respectively

Thus, whereas the waveform presentation resembles those from a commercially available oscilloscope, the newly developed equipment also processes the registered data through wavelet transform, which allowed a more precise evaluation of the time interval elapsed between any two subsequent starts of the current application. The advantage of this additional feature is that the wavelet transform of the signal evidences the instant at which the current application of each of the phases starts. For the case of Figs. 8.a to 8.c although it may seem identifiable that the phase sequence of the current application is A-C-B, because of the significant distortion in the transient waveform of phase B, which is not always possible to happen. In turn, Fig. 9 shows the wavelet transform of that same phase B, on which red circles indicate more precisely the instants at which the current application of each of the indicated phases starts.

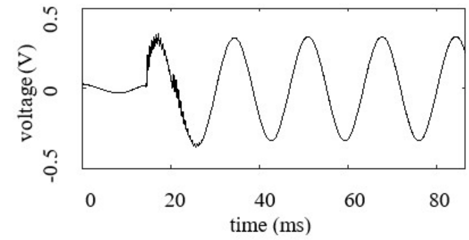


Fig. 9. Wavelet transform of the waveform of Fig. 8.b with indication of phases sequence of operation

In this case, the sequence A-C-B is confirmed, and the measured time interval elapsed between phases A and C could be more precisely evaluated as being 2.47 ms and 3.2 ms between phases C and B, which indicates the circuit breaker to be in good condition.

Despite the encouraging achievements obtained by the research group of which some have been here presented, much is still to be done in adjusting the newly developed equipment for it to reach the desired condition of liability in triggering the electromagnetic signal radiated from the circuit breaker chamber. Thus, because of safety concerns as well as logistics, tests for adjusting the new equipment must be done in situ, which is rarely available, for the reasons given in this work.

5. CONCLUSION

The development of a new measurement unit device for replacing the commercially available digital has become the priority in view of fully guaranteeing that the transient irradiated signals may be captured during every circuit breaker operation. This remarkable conclusion defines the second generation of radiometric measurement systems applied to circuit breaker of which some important results are presented.

Besides triggering concerns, this work shows how important can be the addition of items to the newly developed equipment as the real-time processing of registered data. In this case, this processing was through wavelet transform which has shown as being a powerful tool for evidencing the time interval elapsed between phase current application or interruption. The advanced phase of tests performed in power substations with a prototype of newly developed equipment for replacing the formerly adopted digital oscilloscope has their results here shown.

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REFERENCES

1. Mihalcea, C., Munteanu, F., Nemes, C. & Baiceanu, F. (2019) Lifetime Availability Analysis of High Voltage Circuit Breakers for Maintenance Optimization, *Proc. of 8th International Conference on Modern Power Systems (MPS)* (Cluj-Napoca, Romania), 1–6.
2. Promseela, L., Suwanasri, C., Saribut, S., Suwanasri, T. & Phadungthin, R. (2020) Risk Assessment for Power Circuit Breaker by Using Failure Modes, Effects and Criticality Analysis, *Proc. of International Conference on Power, Energy, and Innovations* (ICPEI) (Chiangmai, Thailand), 149–152.
3. de Souza, F. C., Cabral, S. H. L., Thomas, D. W. P. & Hausmann, R. (2021) ATP Analysis of TRV Applied to the Medium Voltage Circuit of Solar and Onshore Wind Power Plants, *International Journal of Electrical Power & Energy Systems,* **124**, 106364.
4. IEC. (2017) *High-Voltage Switchgear and Controlgear, Standard 62271, Part 100: Alternating-current circuit breakers*, [Online]. Available: https://webstore.iec.ch/en/publication/62785
5. Meier, S. D., Moore, P. J. & Coventry, P. F. (2011). Radiometric Timing of High-Voltage Circuit breaker Opening Operations, *IEEE Transactions on Power Delivery*, **26**(3), 1411–1417.
6. Mustafa, T. I. A. H, Cabral, S. H. L., Meyer, L. H., Almaguer, H. A. D., Puchale, L. H. B., et al. (2022) The Adoption of Ferromagnetic Device for Signal Capturing of Radiometric Measurement Systems, *Proc. of IEEE T&D Conference* (New Orleans, LA).
7. Flurscheim, C. H. (1982) *Power Circuit Breaker Theory and Design*, Stevenage, UK: IET.
8. Giere, S. (2004) *Vakuumschalttechnik im Hochspannungseinsatz* [Vacuum switching technology in high-voltage applications], Göttingen, Germany: Cuvillier Verlag. [In German]
9. Garzon, R. D. (2005) *High Voltage Circuit Breakers: Design and Applications*, Abingdon-on-Thames, UK: Taylor & Francis.
10. Bessonov, L. (1968) *Applied Electricity for Engineers*, Moscow, USSR: MIR.
11. Mustafa, T. I. A. H, Cabral, S. H. L., Meyer, L. H., Almaguer, H. A. D., Pitz, C.A., et al. (2022) A Trigger Method Applied to the Development of Measurement Devices for

Radiometric Measurement Systems, *Proc. of International Conference on Electrical, Computer, Communications and Mechatronics Engineering* (ICECCME) (Maldives), 1–5.

12. Huang, J., Geng, Y., Jin, Q., Chen, X.,Yan, J.. et al. (2022) The Influence of the Dispersion in Pre-arcing Time of Vacuum Circuit Breakers on the Controlled Switching of Capacitor Banks, *Proc. of 6th International Conference on Electric Power Equipment – Switching Technology* (ICEPE-ST) (Seoul, South Korea), 206–211.